

A Joint White Paper Summarizing Results from Independent Simulations of LSST’s NEO Discovery Performance

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Abstract

We summarize the key results of two independent studies that investigated the capabilities of LSST to discover Near-Earth Objects (NEOs). One study was conducted at the Jet Propulsion Laboratory (JPL) on behalf of NASA and the other was from the University of Washington (UW) on behalf of LSST. While the LSST system performance is modeled using similar entering assumptions, the two sets of simulations are otherwise independent of each other.

Both studies concur that LSST’s baseline search strategy of two visits to a given field per night allows successful linking of NEOs in the presence of realistic rates of false detections. The JPL study demonstrated linking numerically with a full-density simulation of 66 million detections over a single observing cycle. The UW study showed through analytic scaling arguments that the computational load of linking nightly pair-wise detections in the presence of significant numbers of false detections will be manageable.

The independent projections for LSST’s NEO completeness agree to within 1–2% when various systematic differences in modeling assumptions are accounted for. Including the contribution of NEO search efforts before and during the LSST survey, the simulations concur that the $H < 22$ NEO catalog will be 75% complete (80% for PHAs) by the end of the 10-year baseline LSST survey. Modeling uncertainties can affect these results by up to $\pm 5\%$. This completeness level could be boosted by a few percent with modest baseline cadence modifications and extended survey duration. Our simulations indicate that a completeness of 90% is likely beyond the reach without major system modifications, such as major cadence changes, significantly extended survey durations, or markedly improved source detection software.

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1. Introduction

This white paper comments on two recent assessment studies of the performance of the Large Synoptic Survey Telescope (LSST) in its planned efforts to detect and catalog near-Earth objects (NEOs). These studies were performed by collaborating but substantially independent groups: one at the Jet Propulsion Laboratory, California Institute of Technology, commissioned by the NASA’s Planetary Defense Coordination Office, and the other an LSST team at the University of Washington. These teams used similar prescriptions to model the LSST system performance (e.g., system throughput and sensitivity, field-of-view, detection efficiency, cadence) but applied fully independent numerical modeling tools. The results of the two studies are reported in the following two draft reports:

- The JPL report is entitled, “Projected Near-Earth Object Discovery Performance of the Large Synoptic Survey Telescope” by S. Chesley & P. Vereš (2017, submitted to NASA HQ).
- The LSST report is entitled, “The Large Synoptic Survey Telescope as a Near-Earth object Discovery Machine” by Jones et al. (2017, to be submitted to *Icarus*).

The purpose of this joint white paper is to highlight the most important results of the studies, and to discuss the extent to which the results of the two reports are in accord.

2. Objectives and Approaches

Both the JPL and UW efforts addressed two overarching questions. The first was to understand how many NEOs could be discovered by LSST under a variety of performance assumptions, with the presumption that LSST would be able to successfully link NEO detections into NEO orbits. The second objective was to evaluate the linking process itself to understand how successful it should be.

2.1. Completeness Projections

A key objective of both studies was to quantify the overall performance of LSST as an NEO discovery system, under the hypothesis that the NEO detections arising from the baseline LSST survey observing cadence can be successfully linked. The latest instantiation of the LSST baseline survey and the most current NEO population model were used to derive the expected fraction of NEOs detected and cataloged by LSST. Both studies employed

similar high-fidelity detection models that accurately represented the LSST focal plane and implemented a smooth degradation in detection efficiency near the limiting magnitude. The studies also carefully modeled losses from trailed detections associated with fast moving objects, and investigated other minor effects, such as telescope vignetting, and asteroid colors and light curves.

The primary metric for assessing the NEO discovery performance was the integral completeness of the orbit catalog for objects having $H < 22$. Objects were considered cataloged if there were at least 3 nights within N days having 2 or more detections within 2 hours. For the various simulations N was 12, 15, 20 or 30 days. Larger N represented increased discovery performance at the expense of increased linking challenge. The crucial question of whether or not these criteria can be met for LSST with high efficiency by available linking engines is discussed below in Sec. 2.2.

As discussed in the reports, modeling assumptions can introduce systematic differences in the estimated completeness. The most important of these are the following:

- When the survey modeling includes the search efforts of past and ongoing NEO search activities, the estimated end-of-survey completeness increases by 15-20% over the naive assumption that LSST operates alone and starts with an empty catalog.
- The completeness is about $\sim 4\%$ lower for NEOs than for PHAs selected as a subset of the same NEO population.
- UW found that increasing the “discovery window” from $N = 15$ to 30 days increases completeness by about 3%. JPL found a similar increase in completeness when extending the window from $N = 12$ to 20 days.

The main differences in the assumptions between the two studies include JPL’s emphasis on NEOs and a 12-day discovery window versus UW’s focus on PHAs and a 30-day discovery window. When these and a few more minor effects are accounted for, the results of the two sets of simulations agree to within 1-2%.

Both studies also investigated a limited number of modifications of the baseline LSST cadence designed to boost NEO completeness. The most effective way to boost the NEO completeness without jeopardizing other LSST mission goals is to extend the survey: for a few years beyond the nominal 10-year survey, the completeness increases about 1-2% per each additional year of surveying (for example, a 4% boost for a 12-year survey).

2.2. Linking Performance

The presence of false detections in the data stream leads to the possibility of high rates of false tracklets, and the ensuing risk that the resulting orbit catalog may be contaminated by false orbits. NEO surveys to date have successfully eliminated this risk by making 3–5 visits per night to obtain confirming detections so that the single-night string of detections has a high reliability. The traditional approach is robust, at the expense of reduced sky coverage and a diminished discovery rate. The baseline LSST approach, in contrast, is potentially fragile to large numbers of false detections, but maximizes the survey performance. One of the key objectives for both studies was to investigate this fragility by exploring the linkage problem. A crucial input to this investigation is the expected false positive detection rate, which was provided by the UW team. This rate was determined using DECam images and prototype LSST image differencing software, as detailed in the Jones et al. study.

The JPL study simulated a full observing cycle (full moon to full moon) with all relevant sources of detections. The resulting 66 million detections were 77% false, and nearly all ($> 99\%$) of the 23% of detections associated with asteroids were of main-belt asteroids. Building tracklets of (primarily) single-night pairs led to 12 million tracklets, of which 57% were false. The final steps of selecting candidate three-night tracks and submitting to orbit determination yielded provided an asteroid orbit catalog with 2180 NEOs, all of which were correctly linked. The simulation obtained orbits for $\sim 94\%$ of theoretically linkable NEOs. A careful tuning of the linking algorithms can be expected to increase this linking efficiency considerably.

In contrast, the UW study explored the linking question from a theoretical perspective using scaling arguments to show that with conservative assumptions LSST should generate roughly 2 million tracklets per night, of which about 75% should be false. The associated estimate of the number of candidate three-night tracks that must be processed depends closely on a number of operational assumptions, but the number is shown to be tractable for the moderate computational resources allocated to the problem.

The 94% linking efficiency reported by JPL was obtained with a few weeks of computation on an 8-core workstation. With appropriately-sized computational resources, some algorithmic improvements and careful tuning of the linking algorithms, the linking efficiency can be significantly improved. (LSST system sizing for analogous computations will provide an equivalent of a 1000-core workstation.) As one of the most important findings, both studies indicate that anticipated false positive detections resulting from image differencing will not jeopardize the two-visits-per-night observing strategy.

3. Discussion

These results, within the hypotheses used in the study, demonstrate that the LSST observation cadence can be successful in cataloging NEOs. This conclusion does assume a certain rate of false positives, but is unlikely to be sensitive to increases by factors of a few in the false detection rate, given the significant computational resources allocated by LSST for the problem.

Taken together, the independent simulations indicate that during its 10-year baseline survey LSST should catalog about 60% of NEOs with absolute magnitude $H < 22$, which is a proxy for 140 m and larger objects. This result assumes a linking window of $N = 15$ days and neglects linking losses and the contribution of any other NEO surveys. (See Table 19 of the JPL report.) Including the worst-case linking efficiency (94%), the expected performance for NEOs with $H < 22$ is about 55% (JPL Table 20). An assessment of systematic modeling errors suggests that the uncertainty on the result at this stage is approximately 5%.

The twin studies used independent approaches to model the contribution of past and ongoing NEO search efforts, and as indicated in Fig. 1, both found that the NEO completeness should be $\sim 43\%$ at the start of the LSST science survey in 2022, and without LSST the ongoing surveys should reach $\sim 60\%$ completeness ten years later. When merging the activities of the ongoing surveys with the LSST survey, the joint effort reaches a completeness of 74-77% at the end of the baseline LSST survey. Thus including the contributions from past and expected future NEO survey activity increases NEO completeness by $\sim 15\%$ over the estimates obtained for LSST operating alone.

When the evaluation of completeness is restricted to so-called Potentially Hazardous Asteroids (PHAs), the completeness increases by up to 5%. Assembling these results leads to a consensus projection that by the end of the 10-year baseline LSST survey the NEO catalog is likely to surpass 80% completeness for PHAs with $H < 22$.

The results above require pairs of observations in three distinct nights over no more than 15 days. A maximum linking interval of 30 days, which should be possible with the substantial computing resources planned for LSST operations, leads to a 3-4% improvement in completeness, and yields 83% for PHAs with $H < 22$. (See Table 3 in the UW report.) As described in detail in the two reports, these results are largely consistent with other results obtained independently.

A special-purpose LSST cadence designed to enhance the NEO discovery rate showed little improvement over the baseline for a 10-year survey. Surveying longer does provide an increase in completeness, by roughly 2% per year for a lone LSST and 1% per year when including contributions from other surveys. Thus, the $H < 22$ PHA catalog delivered by

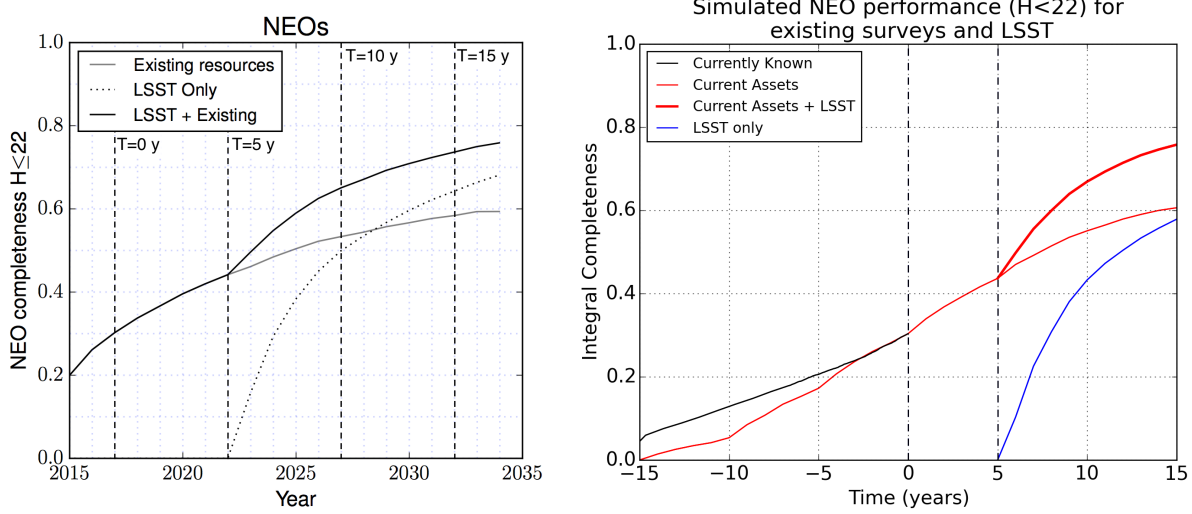


Fig. 1.— Comparable LSST simulation results for NEO completeness from the UW report (left) and the JPL report (right, where the abscissa is relative to Jan. 2017.). Both plots show the modeled performance of existing survey efforts projected into the future, along with the projection for LSST operating alone and in combination with existing efforts. The UW plot assumes 30-day tracks (i.e., a linking window of $N = 30$ days) and thus slightly over-performs on the 15-day track result mentioned in the text, while the JPL plot assumes 12-day tracks, and thus slightly underperforms relative to the 15-day result. The left panel includes vertical dashed lines to facilitate comparison with the right panel.

LSST and other surveys can be expected to reach completeness of about 85% after 12 years of surveying. Both studies conclude that a completeness level of 90% would be beyond reach without major system modifications, such as major cadence changes, significantly extended survey durations, or markedly improved source detection software.

4. Conclusions

The two studies discussed here represent a major undertaking, collectively well over four FTE-years of effort. While there remain open questions and potentially useful avenues for further investigation, both studies agree on the following main conclusions:

1. LSST’s two-visits-per-night observing strategy can be successful in cataloging NEOs. This is based on the false positive detection rate demonstrated from real (DECam) data by Jones et al. The conclusion is unlikely to be sensitive to factors of a few in the false positive rate.

2. Under the assumption that existing NEO surveys continue to operate and see incremental performance improvements, the $H < 22$ NEO catalog can reasonably be expected to surpass 75% completeness following LSST's 10-year baseline survey. PHA completeness may be up to 5 percentage points higher. If LSST continues to operate the baseline cadence beyond 10 years, completeness will increase by about 1% per year of additional surveying up to 5 years.
3. Both simulations indicate that a completeness level of 90% is likely beyond reach without major system modifications or contributions from another next-generation survey.